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A PHOTOGRAPHIC STUDY OF BOILING IN THE ABSENCE OF GRAVITY

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ABSTRACT

A photographic study was made to determine the qualitative effect of zero gravity on the mechanism of boiling heat transfer. The experimental equipment included a container for boiling water and a high speed motion picture camera. To eliminate the influence of gravity, these were mounted on a platform which was allowed to fall freely approximately eight feet. During the free fall, photographs were taken of boiling from various surface configurations such as electrically heated horizontal and vertical ribbons. The heat flux was varied to produce conditions from moderate nucleate boiling to burnout. The results indicate that gravity plays a considerable role in the boiling process, especially in connection with the motion of vapor within the liquid.

INTRODUCTION

The design of power plants and heat exchange equipment for satellite and space vehicles has stimulated an interest in heat transfer phenomena under the conditions of a very small or, in many cases, negligible gravity field. Heat transfer processes such as free convection and film condensation would be expected to be strongly dependent on the body forces due to the gravity field. The boiling process is especially interesting since the dynamics of bubble motion are quite complex and are probably influenced by a number of factors. These include the buoyancy forces

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arising from the gravity field, and the forces resulting from surface tension and from the expansion of vapor into the bubble cavity. It is the purpose of this work to gain some insight into the importance of gravity in the boiling mechanism by making a photographic study of the boiling process in the absence of gravity.

The apparatus includes a high speed motion picture camera and a heated container for boiling water. These are both mounted on a platform which is allowed to fall freely a distance of about eight feet, and motion pictures of the boiling phenomena are taken during this time. During the free fall, the inertia forces of the system exactly balance the forces due to the weight of the body, and hence the boiling takes place in a condition of apparent weightlessness. A variety of boiling conditions were observed. These include nucleate pool boiling from the bottom of a container, and boiling from both horizontal and vertical electrically heated ribbons with various heat fluxes including burnout. Only photographic information was obtained, and no attempt was made for this series of tests to determine numerical magnitudes of heat fluxes or heat transfer coefficients.

EXPERIMENTAL EQUIPMENT

A schematic representation of the apparatus is shown in Fig. 1. The main component in the structure is a platform in the form of a cross, which supports a high speed Fastex motion picture camera and a container for boiling water. At the ends of three branches of the platform there are large guide holes through which 1/4 inch vertical cables pass. The

cables serve as a guide for the falling platform in case of an accident, and during a normal experimental run little or no contact is made between the platform and the cables. A balancing yoke is attached at the top of the platform and can be adjusted so that the solenoid grapple, which holds the platform from above, will be located above the center of gravity of the freely falling equipment.

The features of the apparatus are best described by considering a typical experimental run. A 400 ml beaker is carefully cleaned and partially filled with distilled water. It is then placed on a hot plate which consists of a copper block mounted on a 500 watt electric heater controlled by a Variac. If boiling is to be studied from a horizontal or vertical ribbon the electrical terminals for the ribbon are fastened to the side of the beaker and the ribbon mounted at the desired location in the water. The ribbon power was supplied by a separate 18 amp, 115 volt Variac. The ribbons used were Nichrome, 0.006 inch thick, 0.125 inch wide, and approximately 7/8 inch long. Power was then supplied to both the ribbon and the hot plate under the beaker, and the water was allowed to boil to remove absorbed gases. During the runs where boiling was observed from the ribbon, the heater under the beaker was only used to help maintain the liquid near the saturation temperature and the power was such that very little bubble formation occurred at the bottom of the vessel. The platform was then hoisted eight feet, and final adjustments were made on the heater power to obtain the desired boiling condition.

The drive motor on the camera and the solenoid release grapple which supports the platform are connected to a 6 second Industrial Timer. The

timer will start the camera and then activate the solenoid release in sequence. Generally the camera was started 0.3 seconds before the platform began to drop, and this gave a record of the initial boiling state before the gravity field was removed. The camera speed was generally 3500 to 4000 frames per second, which gave a total running time for 100 feet of film of about 1.25 seconds; 0.3 seconds initially, 0.7 seconds during the free fall, and 0.25 seconds during the deceleration at the end of the run. During some runs the boiling from the ribbon was started at the beginning of the free fall to eliminate any influence of a previous boiling process under normal gravity conditions. This was accomplished very simply by connecting the ribbon heater into the solenoid circuit.

The platform was decelerated by vertical 1/2 inch pipes, fastened to the bottom of the platform, plunging into a bed of sand three feet deep. The sand bed was found to be quite effective in bringing the apparatus to a gradual stop without damage to the camera. The camera was, of course, well supported on the platform.

Adjacent to the boiling container a vertical measuring scale was positioned, so that a continuous record of the vertical location of the platform was recorded on the film. Also the camera recorded timing marks on the film at a rate of 120 per second so that a record of distance versus time was obtained. This indicated that the friction in the system was negligible and that a true free fall was obtained.

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DISCUSSION OF RESULTS

The results are obtained as motion pictures and it is naturally more instructive to view these directly. A loan copy of the film is available on request from the authors. For the purposes of this report sequences of pictures were selected from the film and will serve to illustrate fairly well the description of the boiling process.

Figure 2 shows a series of pictures for pool boiling from the bottom of a glass beaker. The first two pictures in the sequence illustrate the normal boiling process, and the third picture is at the beginning of the free fall. From observing the motion picture films it was noted that there is only a slight inertia associated with the motion of bubbles through the liquid. Following the beginning of the free fall, the bubbles still continued to move a short distance upward and then remained suspended in the liquid. From the sequence of pictures it is seen that large bubbles are formed and increasing quantities of vapor are contained within the liquid during the zero gravity process. The liquid surface is less stable, and as evidenced by the last few pictures in the sequence a liquid film has been pushed up the side of the beaker. It was thought that this film might be in part due to surface tension forces at the liquid glass interface which were no longer balanced by the gravity force. To examine this, a few runs were made using an unheated container, and during the 0.7 second duration of the free fall, the liquid did not move appreciably up the side of the container. However, during boiling the agitation due to the formation and growth of the bubbles pushes liquid up the side and it remains there until the platform is decelerated.

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Figure 3 shows boiling from a horizontal electrically heated ribbon with a moderate heat flux. To eliminate the influence of bubbles formed previous to the free fall, the heating was started at the same moment that the platform was released, so all bubbles were formed under zero gravity conditions. The hot plate under the beaker was used to maintain the fluid near the saturation temperature and a few bubbles were formed at the bottom of the container, but these did not interfere with the vapor formation on the ribbon. The edge of the ribbon is viewed in the pictures, and the flat heating surface extends 1/8 inch into the plane of the paper. Under zero gravity conditions the bubbles remain attached to the ribbon and grow fairly large so that large areas of the ribbon come into contact with vapor. The size which the bubbles attain during the duration of the fall is of course dependent on the magnitude of the applied heat flux. The bubble formation is equally extensive from the bottom surface of the ribbon as from the top.

In Fig. 4 we again have boiling from a horizontal ribbon, but in this case the heat flux has been raised so that the ribbon burns out during the free fall. Also the ribbon is heated previous to the drop, and hence, the first few pictures illustrate the normal boiling process under high heat flux conditions. During zero gravity a single very large bubble is formed roughly 1.5 inches in diameter (beaker diameter is 3 in.). The bubble in this case is located above the ribbon and this may be due to the initial boiling process which caused the water above the ribbon to be at a higher temperature than the water below it. The last

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picture in the sequence shows the ribbon after deceleration. The large bubble which obscured the view of the ribbon has moved out of the liquid and the burned out ribbon can be observed.

Figures 5 and 6 show boiling from a vertical ribbon. The position of the ribbon between the terminal posts is seen in the first picture of Fig. 6. In Fig. 5 the heat flux is at a high level, about 10-20 percent less than that required for burnout. The removal of gravity causes a single large bubble to be formed which is about 2 inches in size.

In Fig. 6 the heat flux has been raised so that the ribbon burns out during the free fall. The heating process is initiated at the beginning of the drop. At the right side of the beaker is a column of bubbles originating from a nucleation center at the bottom of the container, and these bubbles remain suspended in the fluid during the run. In the picture at 0.633 seconds the lower half of the ribbon can be seen glowing, at the beginning of burnout, as a slightly curved white line.

CONCLUDING REMARKS

The photographic study indicates that the gravity field plays a very important role in the removal of vapor from the surface in a normal pool type boiling process. In the situations observed here, the fluid was always near the saturation point and the heat fluxes were sufficiently high to form large quantities of vapor. During the free fall the vapor remained adjacent to the heating surface, and there was no evidence of bubbles being pushed away from the surface to any appreciable extent during their formation. The accumulation of vapor near the surface should

make the electrical heater more sensitive to burnout, but the information obtained in this work is insufficient to make any quantitative statement on this hypothesis. In a situation where the liquid is highly subcooled, so that under ordinary conditions the bubbles form and collapse very close to the heated surface, the removal of gravity would be expected to have much less effect.

Under some circumstances the process with zero gravity may actually be a transient one. If the liquid is at the saturation temperature or slightly superheated, the bubbles at the heating surface may continue to grow indefinitely, and hence larger bubbles would be expected in an experiment with longer free fall times. If the liquid is slightly subcooled there is a chance that a steady state equilibrium can be reached. Under these circumstances the bubbles would increase in size until their surface area is large enough to transfer to the surrounding subcooled liquid the heat being added by the heated surface. Under these conditions the bubbles would remain at a constant size. It appears that a situation like this was reached in Fig. 3.

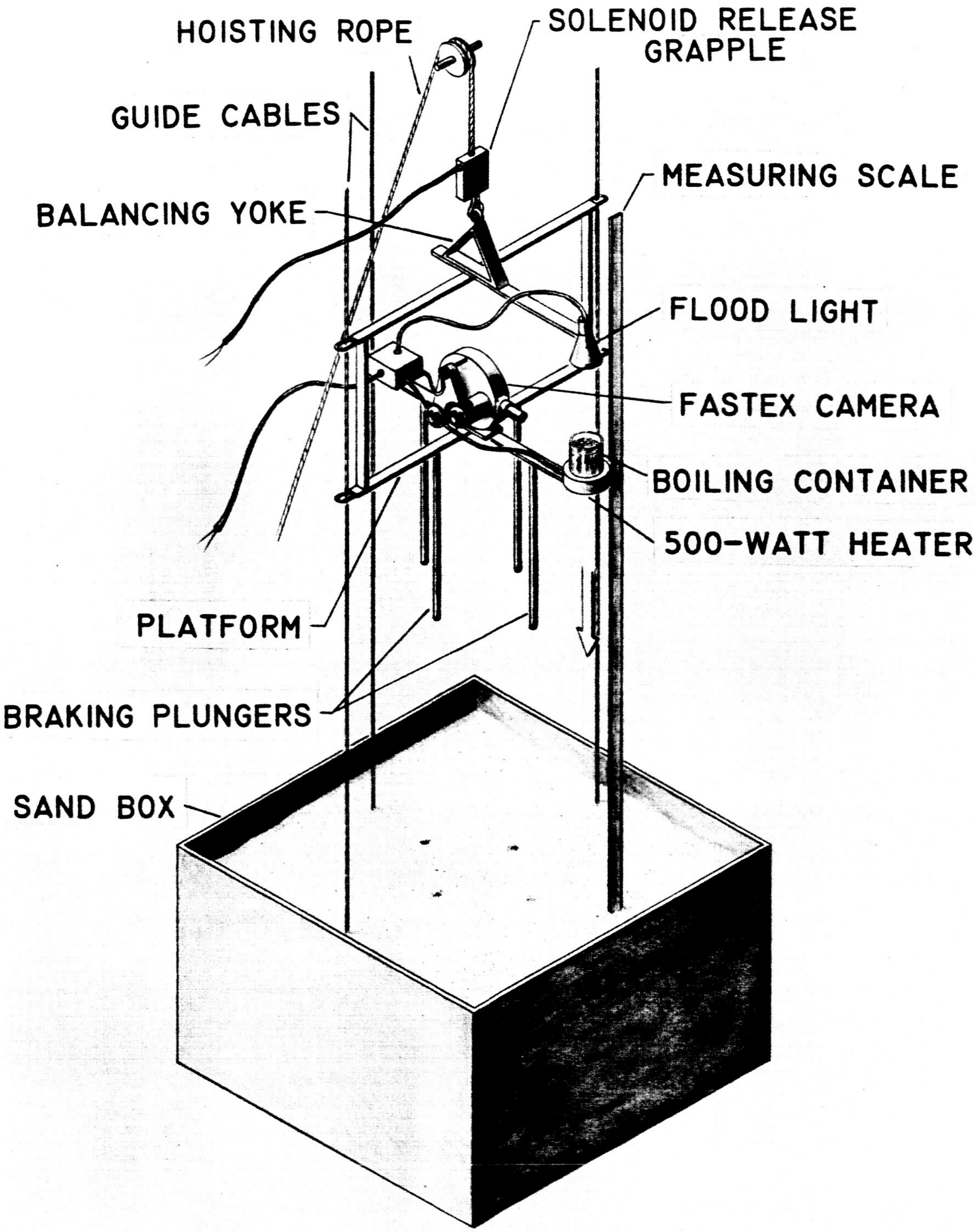

Fig. 1. - Schematic diagram of apparatus.

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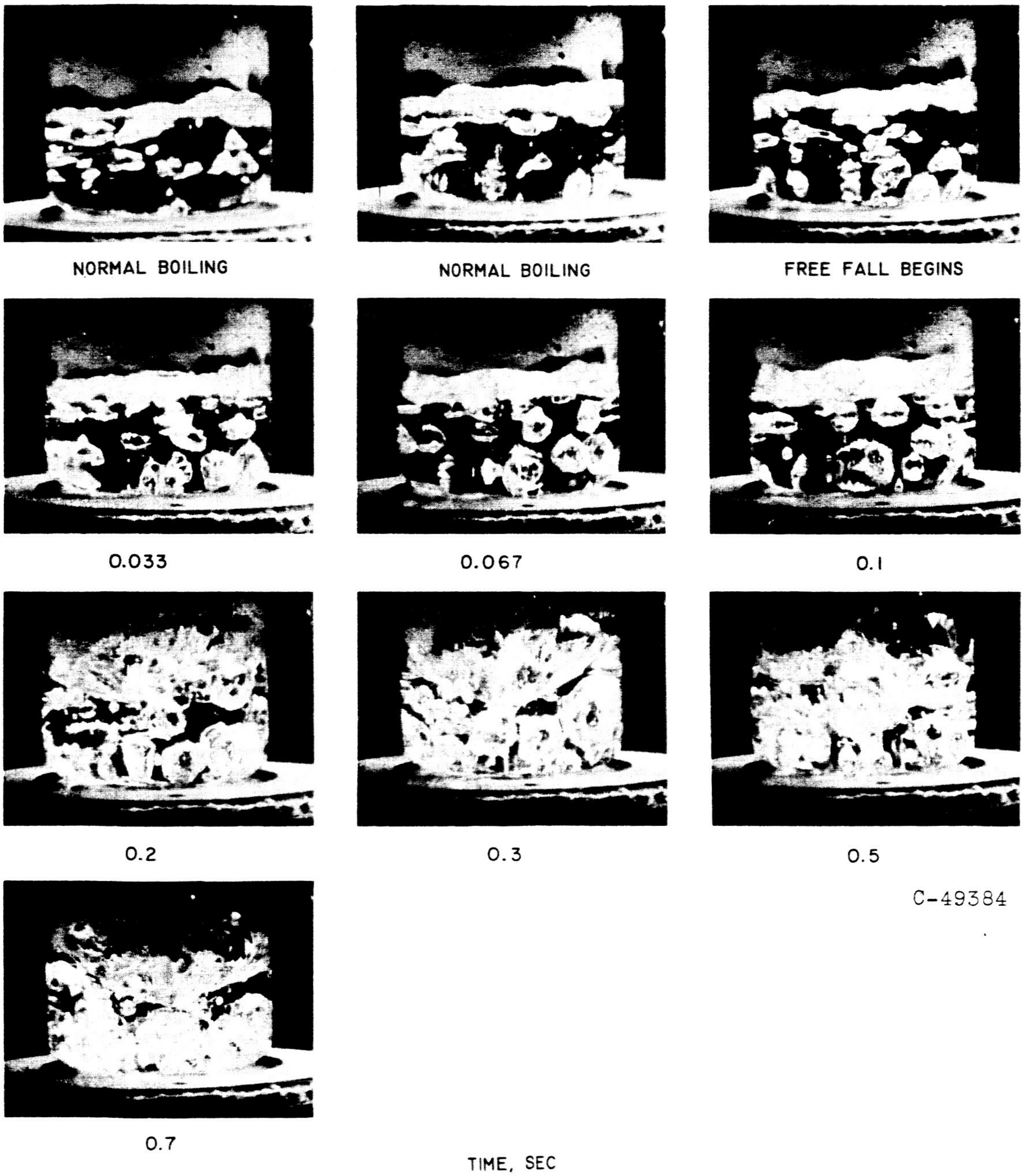

Fig. 2. - Pool boiling from the bottom of a glass beaker.

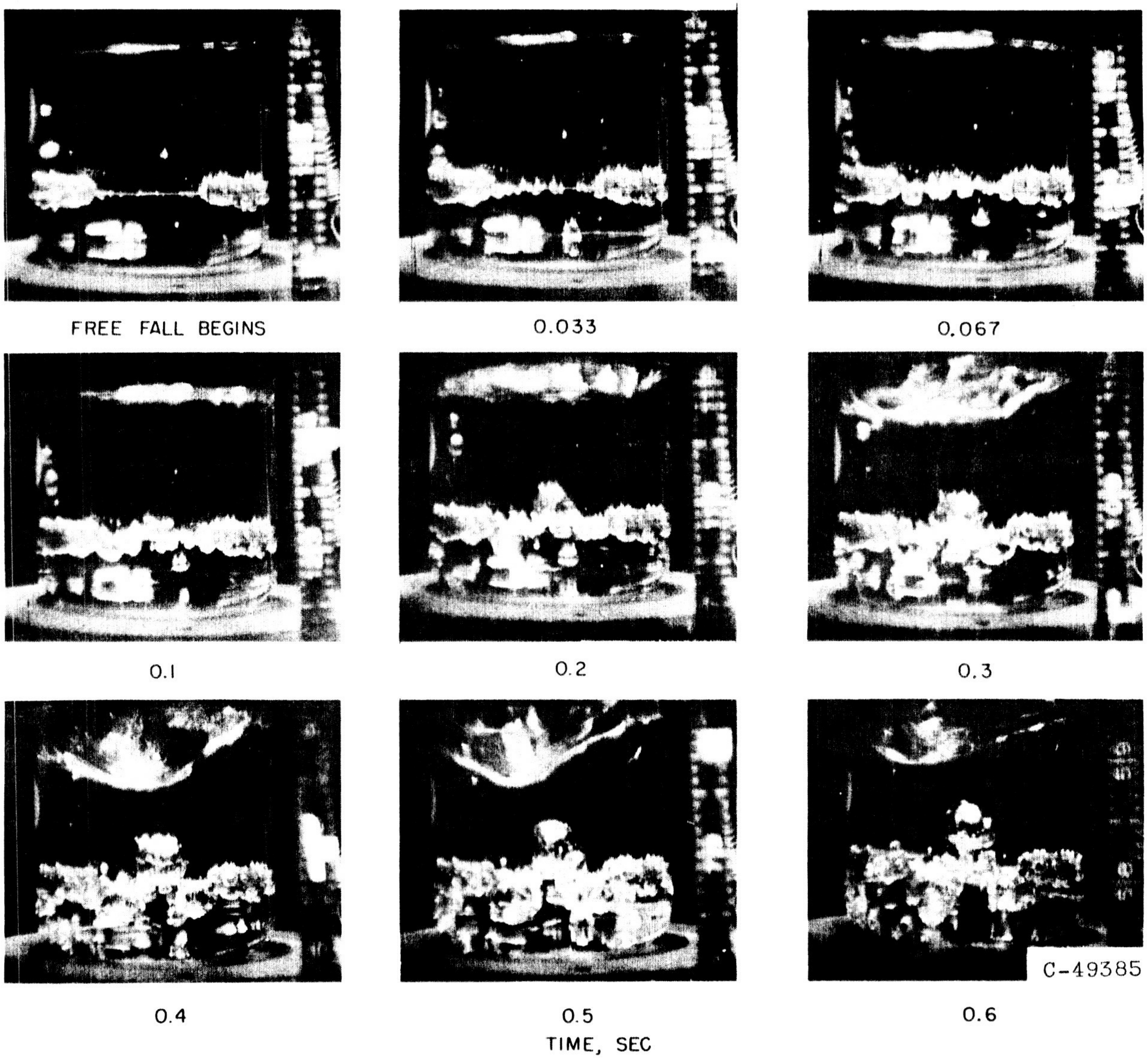

Fig. 3. - Boiling from horizontal electrically heated ribbon with moderate heat flux; heat applied at beginning of free fall.

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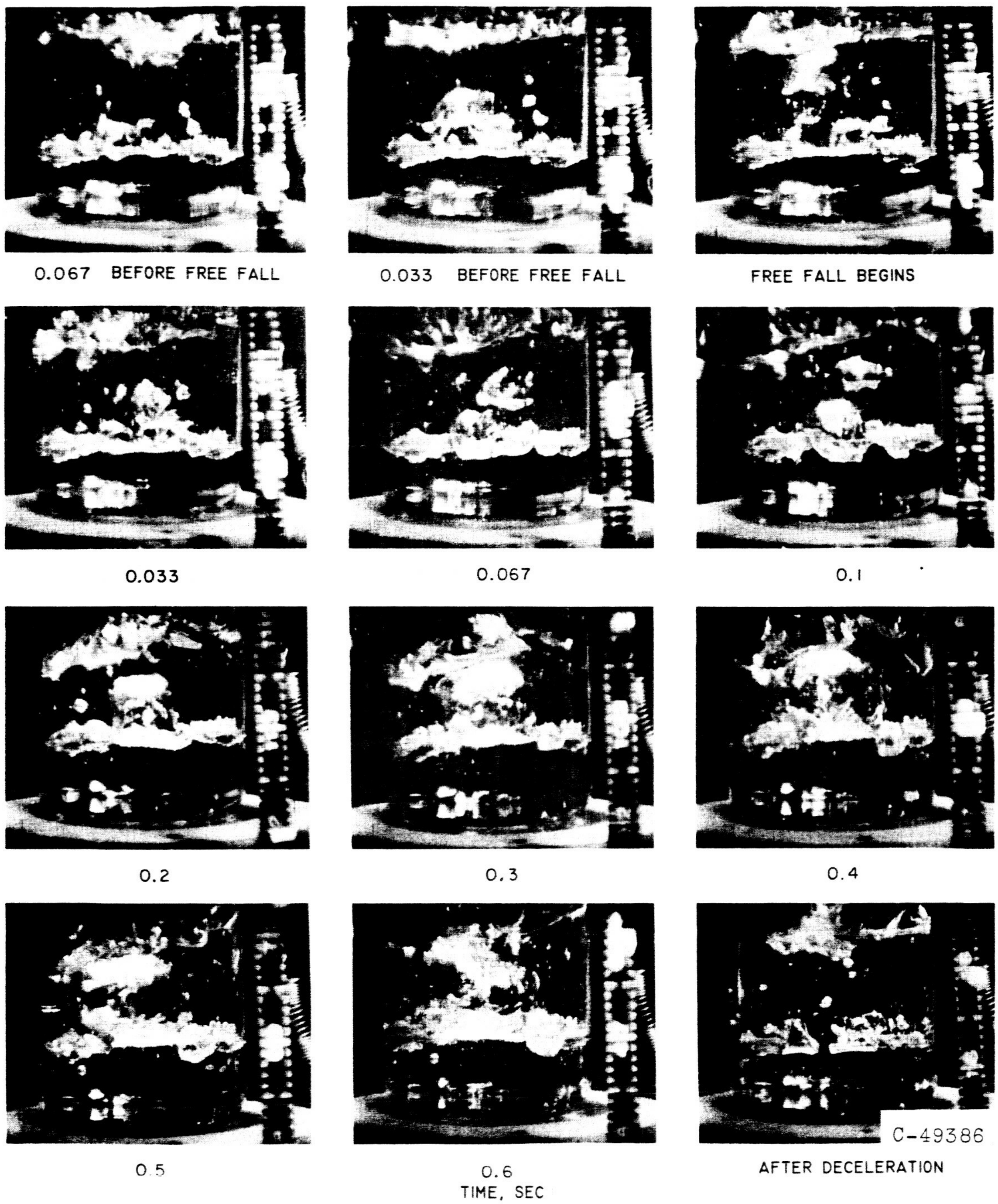

Fig. 4. - Boiling from horizontal electrically heated ribbon with high heat flux and burnout.

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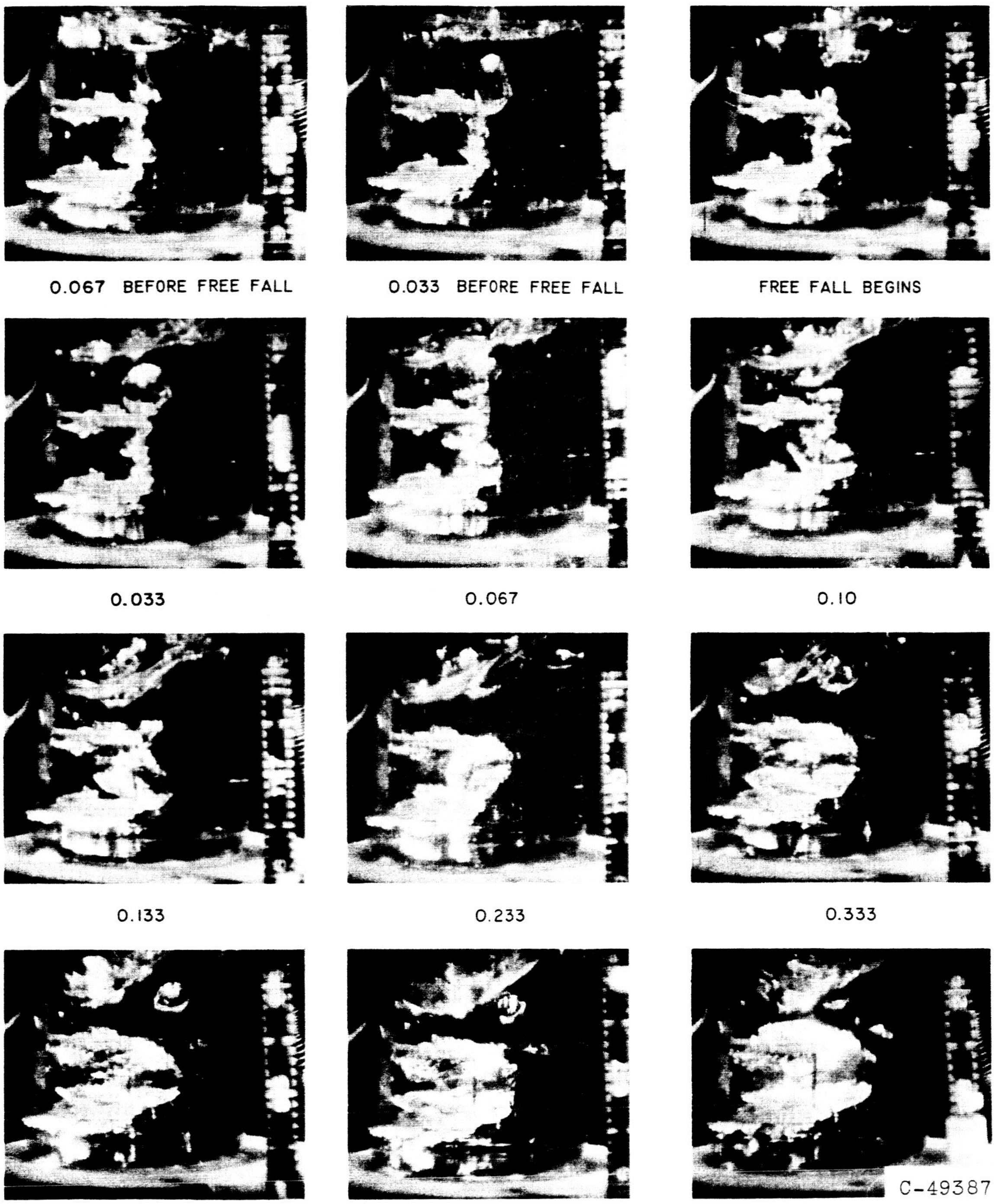

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Fig. 5. - Boiling from vertical electrically heated ribbon with high heat flux.

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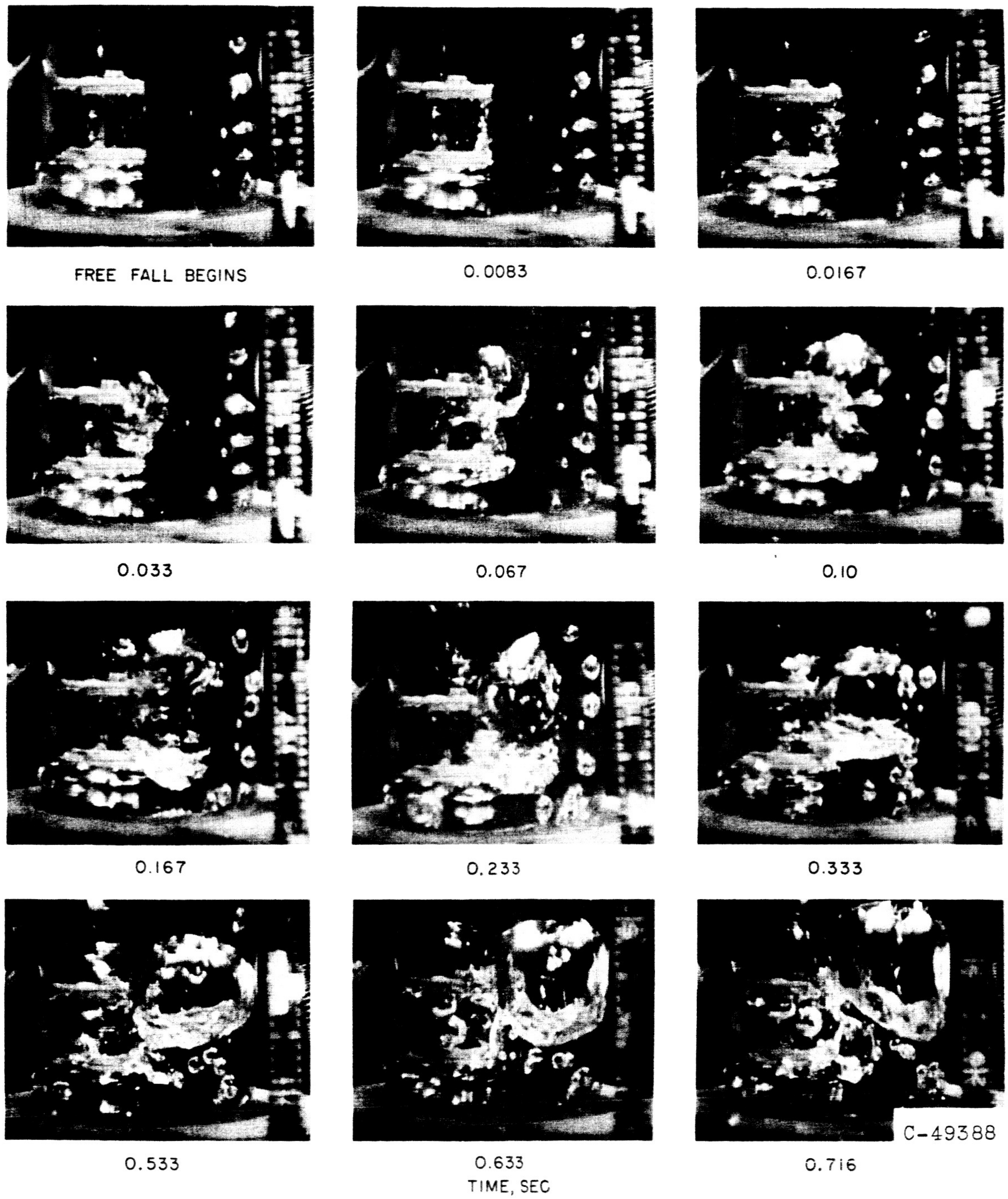

Fig. 6. - Boiling from vertical electrically heated ribbon with high heat flux and burnout; heat applied at beginning of free fall.